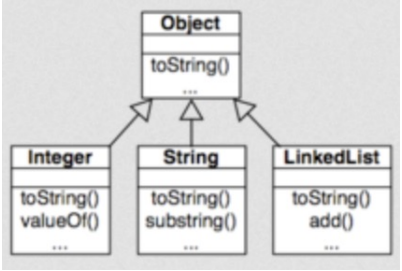
Subtype Polymorphism, Subtyping vs. Subclassing, Liskov Substitution Principle

What is Polymorphism



- Polymorphism is the ability in programming to present the same interface for differing underlying data types.
- Ad-Hoc Polymorphism
  - Functions that can be applied to arguments of different types, but that behave differently depending on the type of the argument to which they are applied
  - Overloading, operator overloading
- Parametric polymorphism
  - A function or a data type to be written generically, so that it can handle values uniformly without depending on their type.
  - C++ Templates, Java Generics
- Subtype polymorphism
  - A name denotes instances of many different classes related by some common superclass
  - Java Subtyping
  - Override

Overriding vs. Overloading

- Method overloading is when two or more methods in the same class have the same name but different parameters
  - When overloading, one changes either the type or the number of parameters for a method that belongs to the same class.
  - Deciding which method to call happens at **compile time**
- Method overriding is when a derived class requires a different definition for an inherited method
  - The method can be redefined in the derived class.
  - In *overriding* a method, the method name and arguments remains exactly the same. The method definition, what the method does, is changed slightly to fit in with the needs of the child class.
  - Java supports *covariant* return types for overridden methods. This means an overridden method may have a *more* specific return type. That is, as long as the new return type is assignable to the return type of the method you are overriding, it's allowed.
  - Deciding which method to call happens at **runtime**

Subtype Polymorphism

- Subtype polymorphism – the ability to use a subclass where a superclass is expected
  - Thus, dynamic method binding
    - `class A { void m() { … } }`
    - `class B extends A { void m() { … } }`
    - `class C extends A { void m() { … } }`
    - Client: `A a; … a.m();` // Call `a.m()` can bind to any of `A.m`, `B.m` or `C.m` at runtime!

override `A.m`

- Subtype polymorphism is the essential feature of object-oriented languages
  - Java subtype: B extends A or B implements I
  - A Java subtype is not necessarily a **true** subtype!

Benefits of Subtype Polymorphism

- Example: Application draws shapes on screen

- Possible solution in C:

```
enum ShapeType { circle, square };
struct Shape { ShapeType t };
struct Circle
{ ShapeType t; double radius; Point center; };
struct Square
{ ShapeType t; double side; Point topleft; };
```

Benefits of Subtype Polymorphism

```
void DrawAll(struct Shape *list[], int n) {
  int i;
  for (i=0; i< n; i++) {
     struct Shape *s = list[i];
     switch (s->t) {
        case square: DrawSquare(s); break;
        case circle: DrawCircle(s); break;
     }
  }
}
```

What's bad about this solution?

Benefits of Subtype Polymorphism

- Example: OO Solution in Java:

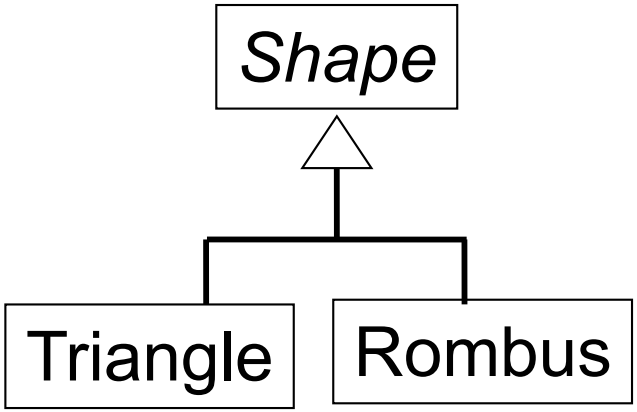
```
abstract class Shape { public void draw(); }
class Circle extends Shape { … draw() }
class Square extends Shape { … draw() }
class Triangle extends Shape { … draw() }
void DrawAll(Shape[] list) {
  for (int i=0; i < list.length; i++) {
     Shape s = list[i];
     s.draw();
  }
}
```

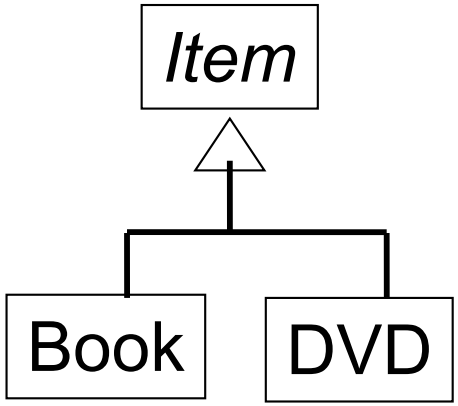
Benefits of Subtype Polymorphism

- Enables extensibility and reuse
  - In our example, we can extend **`Shape`** hierarchy with no modification to the client of hierarchy, **`DrawAll`**
  - Thus, we can reuse **`Shape`** and **`DrawAll`**
- Subtype polymorphism enables the Open/closed principle
  - Software entities (classes, modules) should be open for extension but closed for modification
  - Credited to Bertrand Meyer
- Design Patterns
  - Design patterns promote design for extensibility and reuse
  - Nearly all design patterns make use of subtype polymorphism

Examples of Subtypes

- Subset subtypes
  - Integer is a subtype (subset) of Number
  - range [0..10] is a subtype of range [-10…10]
- Other subtypes
  - Every book is a library item
  - Every DVD is a library item
  - Every triangle is a shape
  - Etc.





What is True Subtyping?

- True Subtyping, conceptually
  - B is subtype of A means every B is an A
    - An is_a relationship
    - Example: every ArrayList is a List
  - In other words, a B object can be substituted where an A object is expected

- Subtypes are substitutable for supertypes
  - Instances of subtypes won't surprise client by requiring "more" than the supertype
  - Instances of subtypes won't surprise client by returning "less" than its supertype
- Java subtyping is realized through subclassing
  - Java subclass is not the same as true subtype!

Subtyping and Subclassing

- Subtyping and substitutability --- specification notions
  - B is a subtype of A if and only if a B object can be substituted where an A object is expected, in any context
- Subclassing and inheritance --- implementation notions
  - B **`extends`** A, or B **`implements`** A
  - B is a Java subclass of A, but not necessarily a true subtype of A!

Subtyping and Subclassing

- Subtype
  - Substitution
  - B is a subtype of A iff an object of type B can masquerade as an object of type A in any context
- Subclass
  - Inheritance
  - Abstracts out repeated code
  - To create a new class just code the differences
  - Every subclass is a Java subtype
    - But not necessarily a true subtype

True Subtype

- We say that (class) B is a true subtype of A if B is a subclass of A and has a stronger specification than A
  - Maybe weaker requirements
  - Maybe stronger results
- Be aware of this when designing inheritance hierarchies!
- Java subtypes that are not true subtypes can be confusing and *dangerous*
  - Can cause subtle, hard to find bugs

True Subtypes

```
public interface Points2D {
  public double x();
  public double y();
}
```



```
public interface Points3D
         extends Points2D {
  public double z();
}
```

- B is a subtype of A means that a B can always be substituted for an A
- A Points3D can always be treated as a Points2D
- Points3D adds a property – the z-coordinate

Subclassing. Inheritance Makes it Easy to Add Functionality

```
class Product {
  private String title;
  private String description;
  private float price;
  public float getPrice() { return price; }
  public float getTax() {
      return getPrice()*0.08f;
  }
}
```

… and we need a class for Products that are on sale

Code cloning is a bad idea! Why?

```
class SaleProduct {
  private String title;
  private String description;
  private float price;
  private float factor; // extends Product
  public float getPrice() {
      return price*factor; } // extends Product
  public float getTax() {
       return getPrice()*0.08f;
  }
}
```

Subclassing

- What's a better way to add this functionality?

```
class SaleProduct extends Product {
    private float factor;
    public float getPrice() {
        return super.getPrice()*factor;
    }
}
```

Subclassing keeps small extensions small

An alternative to SaleProduct extends Product would have been composition!

Composition is a has_a relationship

Benefits of Subclassing

- Don't repeat unchanged fields and methods
  - Simpler maintenance: fix bugs once
  - Differences are clear (not buried under mass of similarity!)
  - Modularity: can ignore private fields and methods of superclass
- Can substitute new implementations where old one is expected (the benefit of subtype polymorphism)
  - Another example: **`Timestamp extends Date`**
- Disadvantage
  - May break equality
    - See Duration example from previous lecture
  - If we implement equality for SaleProduct in the most intuitive way, equality won't be symmetric when comparing a SaleProduct and a Product!

Subclassing Can Be Misused

- Poor planning leads to muddled inheritance hierarchies. Requires careful planning

- If a class is not a true subtype of its superclass, it can surprise client
- If class depends on implementation details of superclass, changes in superclass can break subclass. "Fragile base class problem"

Classic Example of Subtyping vs. Subclassing: Every Square is a Rectangle, right?

Thus, **`class Square extends Rectangle { … }`**

But is a **`Square`** <u>a true subtype</u> of **`Rectangle`**? In other words, is **`Square`** <u>substitutable</u> for **`Rectangle`** in client code?

```
class Rectangle {
  // effects: this_post.width=w,this_post.height=h
  public void setSize(int w, int h);
  // returns: area of rectangle
  public int area();
  …
}
```

Every Square is a Rectangle, right?

```
class Square extends Rectangle { … }
  // requires: w = h
  // effects: this_post.width=w,this_post.height=h
  Choice 1: public void setSize(int w, int h);

  // effects: this_post.width=w,this_post.height=w
  Choice 2: public void setSize(int w, int h);

  // effects: this_post.width=s,this_post.height=s
  Choice 3: public void setSize(int s);

  // effects: this_post.width=w,this_post.height=h
  // throws: BadSizeException if w != h
  Choice 4: public void setSize(int w, int h);
```

Every Square is a Rectangle, right?

- Choice 1 is not good
  - It requires more! Clients of Rectangle are justified to use

```
Rectangle r = new Square();
r.setSize(5, 4);
```

  - In formal terms: spec of **`Square's setSize`** is not stronger than spec of **`Rectangle's setSize`**
    - It weakens Rectangle's setSize spec.
  - Thus, Square can't be substituted for a Rectangle

Every Square is a Rectangle, right?

- Choice 4?
  - It throws an exception that clients of Rectangle are not expecting and not handling
  - If BadSizeException is an unchecked exception, then Java will permit the method to compile, but client code won't expect it.
  - Choice 4 throws a new exception for values in domain. See Specifications.pdf. It shouldn’t throw an exception for values that clients of Rectangle know are OK.
  - Thus, a Square might cause a problem if substituted for a Rectangle

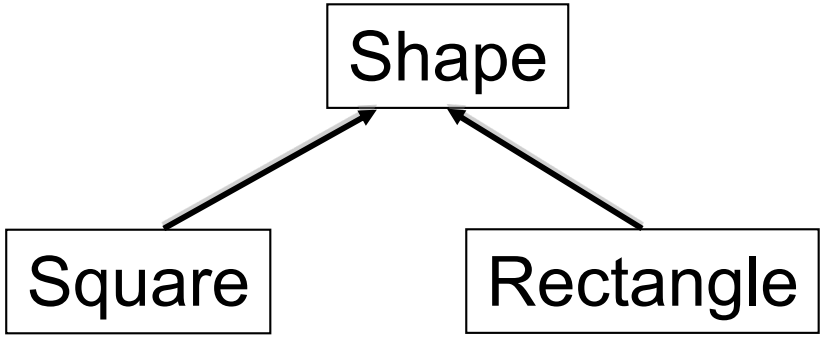
Every Square is a Rectangle, right?

- Choice 3?
  - Clients of Rectangle can write … `r.setSize(5,4).` Square works with `r.setSize(5)`
  - Overload, not an override
  - Square expects all sides to have equal length
  - Clients can break the square invariant by calling the inherited 2-argument setSize method.
    - Client could do **Rectangle r = new Square(); r.setSize(5,4);**

- Choice 2?
  - Client: `Rectangle r = new Square();` … `r.setSize(5,4);` `assert(r.area()==20)  // r.area() returns 25`
  - Again, Square surprises client with behavior that is different from Rectangle's

Every Square is a Rectangle, right?

- Square is not a true subtype of Rectangle
  - Rectangles are expected to have height and width that can change independently
  - Squares violate that expectation. Surprises clients
- Is Rectangle a true subtype of Square?
  - No. Squares are expected to have equal height and width. Rectangles violate this expectation
- One solution: make them unrelated



Liskov Substitution Principle (LSP)

- Due to Barbara Liskov, Turing Award 2008
  - IEEE John von Neumann Medal (2004)
- LSP: A subclass should be substitutable for superclass. I.e., every subclass should be a true subtype of its superclass
- Ensure that B is a true subtype of A by reasoning at the specification level
  - B should not remove methods from A
  - For each B.m that "substitutes" A.m, B.m's spec does not weaken A.m's spec
    - Client: `A a;` … `a.m(int x,int y);` Call `a.m` can bind to B's `m`. B's `m` should not surprise client
  - Any property guaranteed by supertype must be guaranteed by subtype
    - The subtype is permitted to strengthen and add properties
  - Anything provable about A is provable about B
  - If instance of subtype is treated purely as supertype – only supertype methods and fields queried – then result should be consistent with an object of the supertype being manipulated
  - Functions that use pointers or references to base classes must be able to use objects of derived classes without knowing it.

Liskov Substitution Principle Rules

http://www.ckode.dk/programming/solid-principles-part-3-liskovs-substitution-principle/

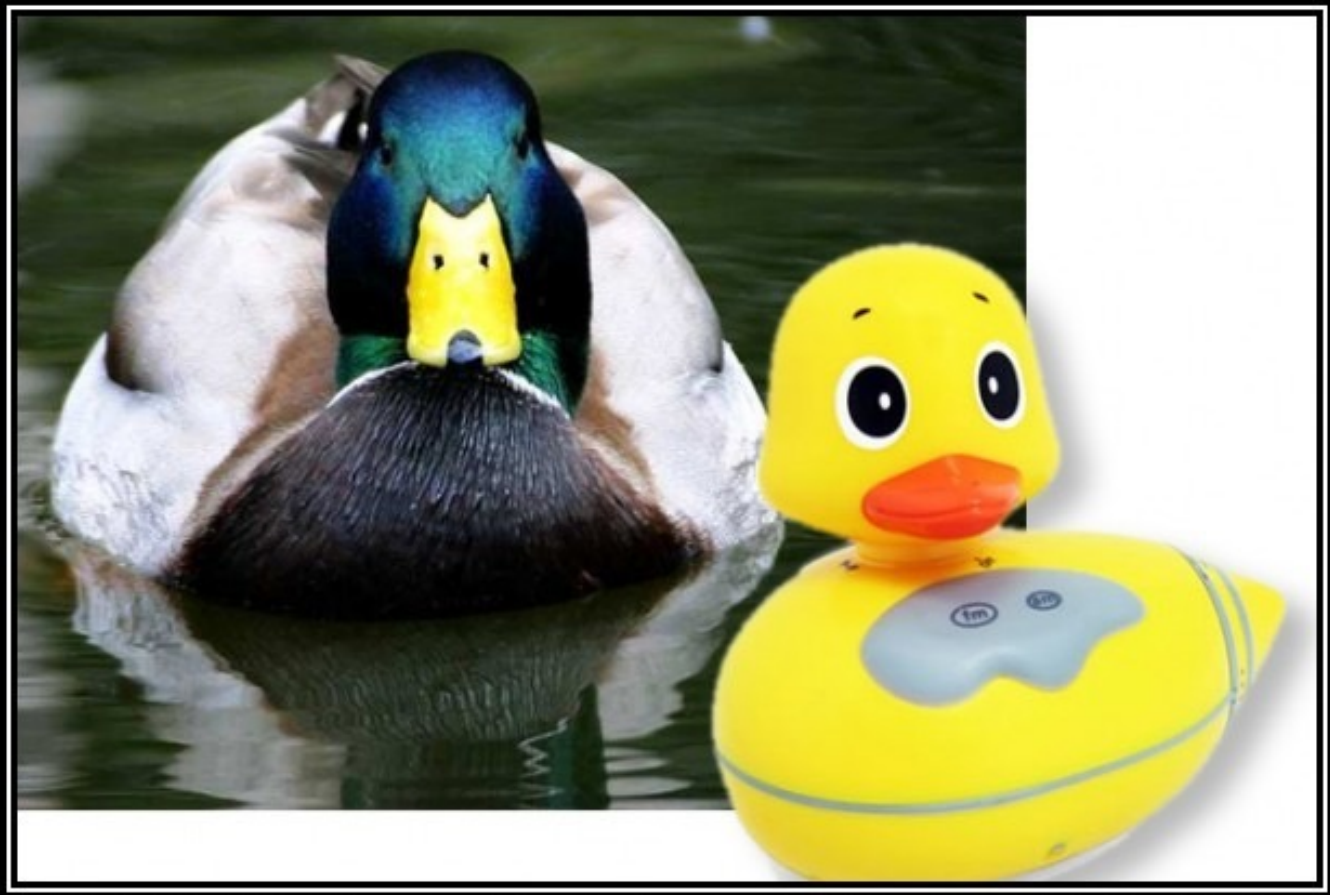
- Contravariance of method arguments in the subtype. (Parameter types of A.m may be replaced by supertypes in subclass B.m.)
  - Java doesn't allow this in overrides
  - Java override method arguments must be invariant
- Covariance of return types in the subtype. (Return type of A.m may be replaced by subtype in subclass B.m)
  - Java override return types are covariant
- No new exceptions should be thrown, unless the exceptions are subtypes of exceptions thrown by the parent. If B.m has weaker preconditions, new unchecked exceptions can be thrown outside A.m's preconditions (See Specifications2.pdf)
- Preconditions cannot be strengthened in the subtype. (You cannot require more than the parent)
- Postconditions cannot be weakened in the subtype. (You cannot guarantee less than the parent)
- Invariants must be preserved in the subtype.
- History Constraint – the subtype must not be mutable in a way the supertype wasn't. For instance MutablePoint cannot be a subtype of ImmutablePoint without violating the History Constraint (as it allows mutations which its supertype didn't)

Substitution Principle for Classes

- If B is a true subtype of A, a B can always be substituted for an A
- Any property guaranteed by supertype must be guaranteed by subtype
  - Subtype can strengthen and add properties
  - Anything provable about A is provable about B
    - A's rep invariant must hold in B
  - If an instance of subtype is treated purely as a supertype (only methods and fields queried) then result should be consistent with results from supertype
- No specification weakening
  - No method removal
    - Not straight forward to do in Java
      - Throw an exception if accessed
  - Overridden methods have a stronger spec

Substitution principle for methods

- Constraints on methods
  - For each method in supertype, subtype may have a corresponding override method
  - May also introduce new methods
- Each overridden method must have a stronger (or equal) spec
  - Ask nothing extra of client
    - Weaker (or equal) precondition
    - Requires clause is at most as strict as supertype requires
    - May substitute supertypes as arguments in some languages
      - Not in Java overrides
      - Java overload
  - Guarantee as much as supertype
    - Stronger (or equal) postcondition
    - Effects clause is at least as strict as supertype
    - No new entries in modifies clause
    - May substitute subtype as return type
  - No new exceptions in domain, unless inside strictly weaker preconditions.



LISKOV SUBSTITUTION PRINCIPLE

If It Looks Like A Duck, Quacks Like A Duck, But Needs Batteries - You Probably Have The Wrong Abstraction

Overload vs. Override – Why do we care?

- Consider this code

```
class MyClass {
        // overload not override
        boolean equals(MyClass m) {
                return true;
        }
}
        Set<MyClass> myClasses = new HashSet<>();
        myClasses.add(new MyClass());
        myClasses.add(new MyClass());
        System.out.println(myClasses.size()); // prints 2?!

        MyClass myClass = new MyClass();
        System.out.println(new MyClass().equals(myClass));  // true

        Object o = new MyClass();
        System.out.println(new MyClass().equals(o));  // false
```

Overload vs. Override – Why do we care?

- You might expect all instances of `MyClass` to be equivalent
- `add()` uses `contains()`
- `contains()` uses `hashCode()` to determine bin
  - `myClasses.add(new MyClass());`
  - `myClasses.add(new MyClass());`
  - Different hashCodes
- `new MyClass().equals(o)` returns false
  - At runtime, JVM looks for `equals(Object o)`
  - `equals(Object o)` uses reference equality
- Override *redefines* the method.
- Overload defines an entirely new method

Aside: Why doesn't Java allow contravariant parameters in overrides?

- Java and C++ don't allow contravariant arguments
  - It makes resolving what method to call more complicated

```
class A {
    public void f(String s) {...}
    public void f(Integer i) {...}
}

class B extends A {
    public void f(Object o) {...} // Which A.f should this override?
}
```

…

  - Some languages allow contravariant arguments
    - Sather, OCaml

Box is a BallContainer?

```
class BallContainer {
 // modifies: this
 // effects: adds b to this container if b is not
 //          already in
 // returns: true if b is added, false otherwise
 public boolean add(Ball b);
 …
}
class Box extends BallContainer { // good idea?
 // modifies: this
 // effects: adds b to this Box if b is not
 //          already in and this Box is not full
 // returns: true if b is added, false otherwise
 public boolean add(Ball b);
 …
}
```

Box is a BallContainer?

- So, is `Box` a true subtype of `BallContainer`?
- No. Client is justified writing this code:

```
BallContainer c = new Box();
while (i++<100) { c.add(new Ball(20)); }
assert(c.getVolume() == 2000)
```

  - May fail if capacity of Box is exceeded

- Can't substitute `Box` for `BallContainer`. It guarantees less.
  - Returns false in cases where supertype would return true.

Summary So Far

- Java subtypes (realized with extends, implements) must be true subtypes
  - Java subtypes that are not true subtypes can be confusing and lead to difficult to find bugs.
- When B is a Java subtype of A, ensure
  - B does not remove methods from A
  - A substituting method B.m has stronger spec than method A.m which it substitutes
  - Guarantees substitutability
    - If B is a true subtype of A, a B can always be substituted for an A
- Liskov Substitution Principle is a principle, not a command
  - Java doesn't allow contravariant arguments in overrides
    - Override - method to be called is determined at runtime
    - Overload - method signature corresponds to a different method family

Type Signature is a Specification

- Type signature (parameter types + return type) is a contract too

E.g., **`double f(String s, int i) {…}`**

Precondition: arguments are a **`String`** and an **`int`**

Postcondition: result is a **`double`**

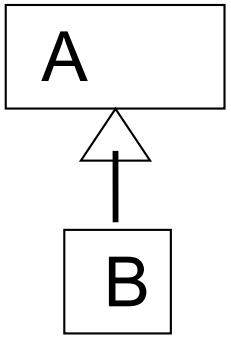
- We need reasoning about behavior and effects, so we added requires, effects, etc.

Function Subtyping, in general

- In programming languages, function subtyping deals with substitutability of functions
  - Question: under what conditions on the parameter and return types A,B,C and D, is function A f(B) substitutable for C f(D)
  - Reason at the level of the type signature
  - Rule: A f(B) is a function subtype of C f(D)
    - if A is a subtype of C and B is a supertype of D
      - A could be a subtype of C and B the same type as D
        - This is only case Java allows for overrides
      - B could be a supertype of D and A the same type as C
        - Java overload
    - Guarantees substitutability
    - Specification
      - Return type is stronger
      - Argument type is weaker
        - The same type for Java overrides

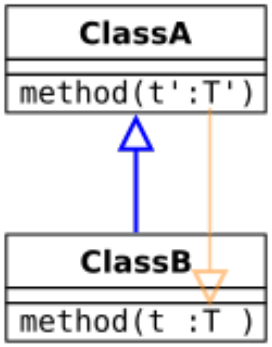
Type Signature of Substituting Method is Stronger

- Method parameters (inputs) in object-oriented languages:
  - Parameter types of A.m may be replaced by supertypes in subclass B.m. "contravariance"
    - E.g., A.m(String p) and B.m(Object p)
  - B.m places no extra requirements on the client!
    - E.g., client: **`A a;`** … **`a.m(q)`**. Client knows to provide **`q`** a String.
    - In languages which allow this, client code will work fine with **`B.m(Object p)`**, which asks for less: an Object, and clearly, every String is an Object
  - Java does not allow change of parameter types in an *overriding* method



```java
class Animal {
        String name;

        Animal(String name) {
                this.name = name;
        }
        void sayHello(Giraffe g) {
                System.out.println("Animal.sayHello: My name is " + name);
        }
}
class Giraffe extends Animal {
        Giraffe(String name) {
                super(name);
        }

        void sayHello(Animal g) {
                System.out.println("Giraffe.sayHello: My name is " + name);
        }
}

public class ContraVariance {
      public static void main(String[] args) {
            Animal a = new Animal("Generic Animal");
            Animal g = new Giraffe("Alice");
            g.sayHello(a);  // compiler error
            g.sayHello(g);  // also an error
      }
}
```

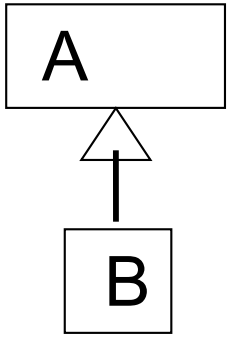
Contravariant Arguments



- Doesn't work in Java overrides
  - `sayHello()` is an overload
  - At compile time `a` and `g` belong to the `Animal` class
  - There is no method `Animal.sayHello(Animal)`
  - C++ treats functions with contravariant arguments as overloads
  - Sather language allows contravariant argument types
- Java treats contravariant arguments as overloads, not overrides
  - Method family determined at compile time
  - Compiler determines that `a` and `g` are animals at compile time

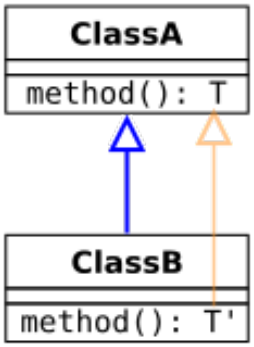
Type Signature of Substituting Method is Stronger

- Method returns (results):
  - Return type of A.m may be replaced by subtype in subclass B.m. "covariance"
    - E.g., Object A.m() and String B.m()
  - B.m does not violate expectations of the client!
    - Result type of A.m() may be replaced by a subtype in B.m() in the subclass
      - Doesn't violate client expectations
    - E.g., **`Object o = a.m()`**. Client expects an **`Object`**. Thus, **`String`** will work fine
    - `String` is an `Object`
  - No new exceptions. Existing exceptions can be replaced by subtypes
  - Java does allow a subtype return type in an overriding method!



```java
class Animal {
        String name;

        Animal(String name) {
                this.name = name;
        }

        Animal cloneIt() {
                return new Animal(name);
        }
}

class Giraffe extends Animal {
        Giraffe(String name) {
                super(name);
        }

        Giraffe cloneIt() {
                return new Giraffe(name);
        }
}

public class Covariant {

        public static void main(String[] args) {
                Animal a = new Giraffe("Alice");
                Animal g = a.cloneIt(); // OK

                g.sayHello();
        }
```

Covariant Return Type



- Covariant (subclass) return types are safe
  - Java override
  - Dynamic
    - Determined at runtime
  - Stronger return type

- Java overrides
  - Invariant argument types
  - Covariant return types

Properties Class from the JDK

`Properties` stores String key-value pairs. It extends **`Hashtable`** so **`Properties`** is a Java subtype of **`Hashtable`**. What's the problem?

```
class Hashtable {
 // modifies: this
 // effects: associates value with key
 public void put(Object key, Object value);
 // returns: value associated with key
 public Object get(Object key);
}
class Properties extends Hashtable { // simplified
 // modifies: this
 // effects: associates String value with String key
 public void put(String key, String value) {
    super.put(key, value);
 }
 // returns: value associated with key
 public String get(String key) {
    return (String) super.get(key);
 }
```

Exercise

```
class Hashtable {
   public void put(Object key, Object value);
   public Object get(Object key);
}

class Properties extends Hashtable {
   public void put(String key, String value);
   public String get(String key);
}
```

Exercise

```
class Product {
   Product recommend(Product p);
}
```

Which one is a function subtype of **`Product.recommend?`**

```
class SaleProduct extends Product {
   Product recommend(SaleProduct p);
   SaleProduct recommend(Product p);
   Product recommend(Object p);
   Product recommend(Product p) throws
                                 NoSaleException;
}
```

Exercise

```
class Product {
   Product recommend(Product p);
}
```

Which one is a function subtype of **`Product.recommend?`**

```
class SaleProduct extends Product {
   Product recommend(SaleProduct p); // overload
   SaleProduct recommend(Product p); // OK
   Product recommend(Object p); // OK but overload
   Product recommend(Product p) throws
                        NoSaleException; // bad
}
```

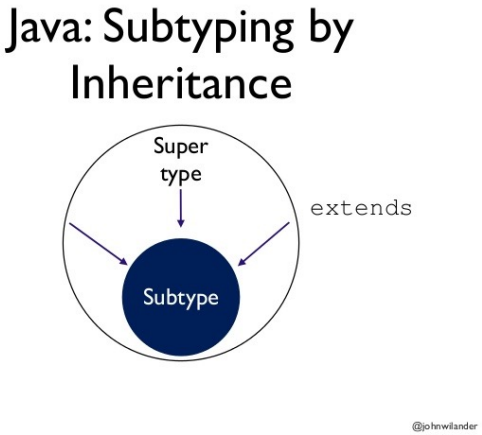
Reasoning about Specs

- Function subtyping reasons with type signatures
- Remember, type signature is a specification!
  - Precondition: requires arguments of given type
  - Postcondition: promises result of given type
- Compiler checks function subtyping
- Behavioral specifications add reasoning about behavior and effects
  - Precondition: stated by requires clause
  - Postcondition: stated by modifies, effects, returns and throws clauses
- To ensure A is a true subtype of B, we must reason about behavioral specifications (as we did earlier)

Reason about Specs

- Behavioral subtyping generalizes function subtyping
- B.m is a true function subtype (behavioral subtype) of A.m
  - B.m has <u>weaker</u> precondition than A.m
    - Contravariance
  - B.m has <u>stronger</u> postcondition than A.m
    - Generalizes "B.m's return is a <u>sub</u>type of A.m's return"
    - Covariance
  - These 2 conditions guarantee B.m's spec is stronger than A.m's spec, and B.m is substitutable for A.m
    - All other things being equal

Java Subtypes



- Java types are defined by <u>classes</u>, <u>interfaces</u>, primitives
- Java subtyping stems from declarations
  - B **`extends`** A
  - B **`implements`** A
- In a Java subtype, a "substituting" method is an overriding method
  - <u>Has same parameter types</u>
  - Has compatible (same or subtype) return type
  - Has no additional declared exceptions

Overloading vs. Overriding

- If a method has same name, but different parameter types, it overloads not overrides

```
class Hashtable {
   public void put(Object key, Object value);
   public Object get(Object key);
}
class Properties extends Hashtable {
   public void put(String key, String value);
   public String get(String key);
}
```

overload Hashtable's put and get

Overloading vs. Overriding

- A method family contains multiple implementations of same name + parameter types (but not necessarily the same return type!)
- Which method family? is determined at compile time based on compile-time types
  - E.g., family put(Object key, Object value)
    - or family put(String key, String value) // different family
- Which <u>implementation</u> from the method family runs, is determined at runtime based on the runtime type of the receiver

Java Types

- Java objects have two types
  - **Compile time** type
    - Also called declared type
    - Also called static type
    - Also called apparent type
    - Compiler determines
  - **Runtime** type
    - Also called actual type
    - Also called dynamic type
    - Looked up in heap
- Runtime type must be the same as compile time type or subtype of compile time type

Static and Dynamic Types

- B extends A and C extends B.
- The dynamic type of an object (the type used after the *new* statement) is its *runtime* type
  - it defines the actual methods that are present for an object.
- The static type of an object reference (a variable) is a *compile-time* type
  - Also called the apparent type
  - it declares which methods can be called on the object that the variable references.
- The static type of a variable should always be of the same type or a supertype of the dynamic type of the object it references.
  - Runtime type is the same or a subtype of the compile time type
- Java Language Spec on method invocation is complex

Java Subtyping Guarantees

- A variable's runtime type (i.e., the class of its runtime object) is a Java subtype of the variable's declared class (Not true in C++!)

```
Object o  = new Date(); // OK
Date d = new Object(); // Compile-time error
```

- Thus, objects always have implementations of the method specified at the call site
  - Client: `B b;` … `b.m()` // Runtime object has `m()`
  - If all subtypes are true subtypes, spec of runtime target `m()` is stronger than spec of `B.m()`

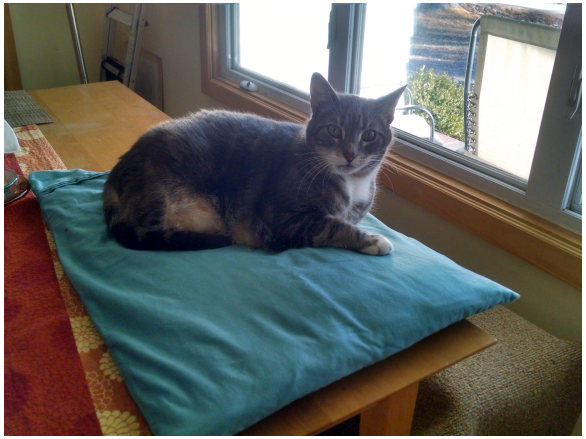
How does a Method Call Execute?

- For example, `x.foo(5);`
- Compile time
  - Determine what class to look in – compile time class
    - Look at static type of receiver (`x` above)
  - Determine the method signature (family)
    - Find all methods in the class with the right name
    - Includes *inherited* methods
      - Look for overrides, return type may be a subtype
  - Keep only methods that are *accessible* and *applicable*
    - e.g. a private method is not accessible to calls from outside the class
    - The types of the actual arguments (e.g. 5 has type int above) must be subtypes of the corresponding formal parameter type
  - Select the most specific method
    - m1 is more specific than m2, if each argument of m1 is a subtype of the corresponding argument of m2
  - Keep track of the method's signature (argument types) for run-time

How does a Method Call Execute?

- Run time
  - Determine the run-time type of the *receiver*
    - `x` in this case
    - Look at the object in the heap to find out what its run-time type is
  - Locate the method to invoke
    - Starting at the run-time type, look for a method with the right name and argument types found statically, i.e. method family
      - The types of the actual arguments may be subtypes of the corresponding formal parameter type
    - If it is found in the run-time type, invoke it.
    - Otherwise, continue the search in the superclass of the run-time type
    - Look only at family members
    - This procedure will always find a method to invoke, due to the checks done during static type checking

Example



```
class GenericAnimal {
   public String talk() {
   return "Noise"; }
}

class Bird extends GenericAnimal {
   public String talk(){
   return "Chirp"; }
}

class Cat extends GenericAnimal {
   public String talk(){
   return "Meow"; }
}

class Dog extends GenericAnimal {
   public String talk(){
   return "Woof"; }
}

class GizmoTheCat extends Cat {
   public String talk(){
   return "Hello, I would like some oatmeal."; }
}
```

```
public class AnimalTalk {
        public static void main(String[] args) {
                GenericAnimal A = new GenericAnimal();
                System.out.println(A.talk());

                GenericAnimal B = new Bird();
                System.out.println(B.talk());

                GenericAnimal C = new Cat();
                System.out.println(C.talk());

                GenericAnimal G = new GizmoTheCat();
                System.out.println(G.talk());

                // what does this print?
                GizmoTheCat G2 = new GizmoTheCat();
                GenericAnimal F = G2;  // Compile time type? Runtime type?
                System.out.println(F.talk());

        }
}
```

Remember **Duration**

Two method families.

```
class Object {
   public boolean equals(Object o);
}
class Duration {
   public boolean equals(Object o);  // override
   public boolean equals(Duration d);
}
Duration d1 = new Duration(10,5);
Duration d2 = new Duration(10,5);
System.out.println(d1.equals(d2));
// Compiler choses family equals(Duration d)
```

Remember **Duration**

```
class Object {
   public boolean equals(Object o);
}
class Duration {
   public boolean equals(Object o);
   public boolean equals(Duration d);
}
Object d1 = new Duration(10,5);
Duration d2 = new Duration(10,5);
System.out.println(d1.equals(d2));
// At compile-time: equals(Object o)  (method family)
// At runtime: Duration.equals(Object o)
```

Remember **Duration**

```
class Object {
   public boolean equals(Object o);
}
class Duration {
   public boolean equals(Object o);
   public boolean equals(Duration d);
}
Object d1 = new Duration(10,5);
Object d2 = new Duration(10,5);
System.out.println(d1.equals(d2));
// Compiler choses equals(Object o)
// At runtime: Duration.equals(Object o)
// receiver type is Duration at runtime
```

Remember **Duration**

```
class Object {
   public boolean equals(Object o);
}
class Duration {
   public boolean equals(Object o);
   public boolean equals(Duration d);
}
Duration d1 = new Duration(10,5);
Object d2 = new Duration(10,5);
System.out.println(d1.equals(d2));
// Compiler chooses equals(Object o)
// At runtime: Duration.equals(Object o)
// receiver type is Duration at runtime
```

Exercise

```
class Y extends X { … }

class A {
   X m(Object o) { … }
}
class B extends A {
   X m(Z z) { … }
}
class C extends B {
   Y m(Z z) { … }
}
```

```
A a = new B();
Object o = new Object();
// Which m is called?
X x = a.m(o);
```

```
A a = new C();
Object o = new Z();
// Which m is called?
X x = a.m(o);
```

Exercise

```
class Y extends X { … }
class W extends Z { … }
class A {
   X m(Z z) { … }
}
class B extends A {
   X m(W w) { … }
}
class C extends B {
   Y m(W w) { … }
}
```

```
A a = new B();
W w = new W();
// Which m is called?
X x = a.m(w);
```

```
B b = new C();
W w = new W();
// Which m is called?
X x = b.m(w);
```

Subclassing is Difficult

Before:

```
class B {
   private int c=0;
   void inc1() { c++; }
   void inc2() { c++; }
}
class A extends B {
   @Override
   void inc2() {
     inc1();
   }
}

public class IncTest {
    public static void
        main(String[] args) {
      A a = new A();
      a.inc2();
      System.out.println(a.get());
   }
}
```

After a tiny change:

```
class B {
   private int c=0;
   void inc1() { inc2(); }
   void inc2() { c++; }
}
class A extends B {
   @Override
   void inc2() {
     inc1();
   }
}
```

Fragile Base Class Problem

- Previous slide showed an example of the Fragile Base Class Problem
- Occurs when the implementation of a subclass depends on implementation details in the superclass. Seemingly innocuous changes in the superclass can break the subclass

Subclassing is Difficult

- A set that counts the number of attempted additions:

```
class InstrumentedHashSet extends HashSet {
  private int addCount = 0;
  public InstrumentedHashSet(Collection c) {
   super(c);
  }
  public boolean add(Object o) {
   addCount++; return super.add(o);
  }
  public boolean addAll(Collection c) {
   addCount += c.size(); return super.addAll(c);
  }
  public int getAddCount() { return addCount; }
}
```

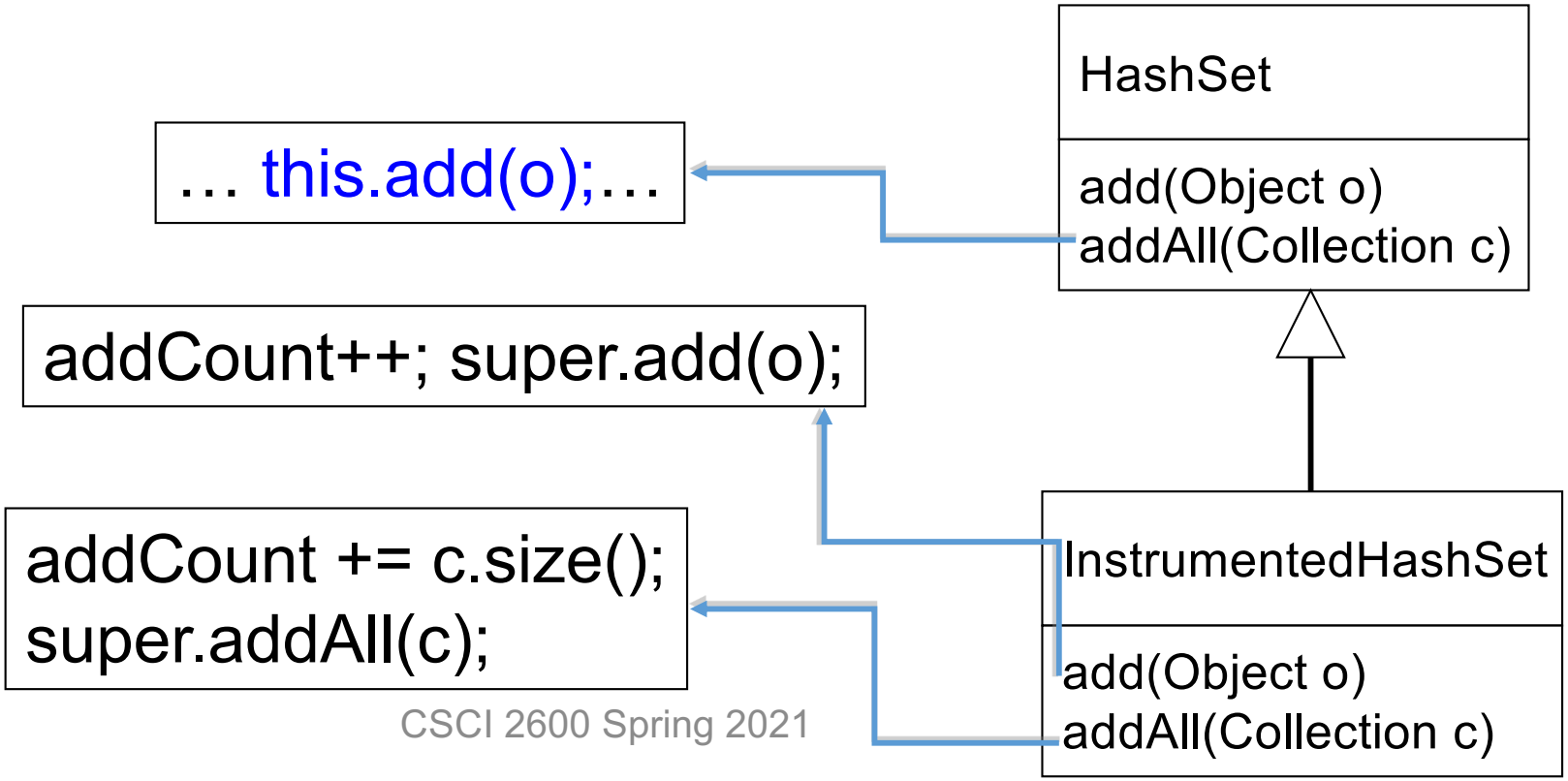
Subclassing is Difficult

- **`InstrumentedHashSet`** is a true subtype of **`HashSet`**. But… Something goes quite wrong here

```
class InstrumentedHashSet extends HashSet {
  private int addCount = 0;
  public InstrumentedHashSet(Collection c) {
   super(c);
  }
  public boolean add(Object o) {
   addCount++; return super.add(o);
  }
  public boolean addAll(Collection c) {
   addCount += c.size(); return super.addAll(c);
  }
  public int getAddCount() { return addCount; }
}
```

Subclassing is Difficult

```
InstrumentedHashSet s = new InstrumentedHashSet();
System.out.println(s.getAddCount()); // 0
s.addAll(Arrays.asList("One","Two"));
System.out.println(s.getAddCount()); // Prints?
```



The Yo-yo Problem

- **`this.add(o)`** in superclass **`HashSet`** calls **`InstrumentedHashSet.add`**! Callback.

- Example of the yo-yo problem. Call chain "yo-yos" from subclass to superclass back to subclass
  - **`InstrumentedHashSet.addAll`** calls **`HashSet.addAll`** calls **`InstrumentedHashSet.add`**
- Behavior of **`HashSet.addAll`** depends on subclass **`InstrumentedHashSet`**!

Java Subtyping with Interfaces

Why Set and not HashSet?
Avoid implementation detail

```
class InstrumentedHashSet implements Set {
  private final Set s = new HashSet();
  private int addCount = 0;
  public InstrumentedHashSet(Collection c) {
   this.addAll(c);
  }
  public boolean add(Object o) {
   addCount++; return s.add(o);
  }
  public boolean addAll(Collection c) {
   addCount += c.size(); return s.addAll(c);
  }
  public int getAddCount() { return addCount; }
  // … Must add all methods specified by Set
}
```

Java Subtyping with Interfaces

- interface inheritance
  - Client codes against type signature of interface methods, not concrete implementations
  - Behavioral specification of an interface method often unconstrained
    - Often, any (later) implementation is stronger!
  - Facilitates composition and wrapper classes as in the **`InstrumentedHashSet`** example

Java Subtyping with Interfaces

- In JDK and the Android SDK
  - Implement multiple interfaces, extend single abstract superclass (very common!)
    - Abstract classes minimize number of methods new implementations must provide
    - Abstract classes facilitate new implementations
    - Using abstract classes is optional, so they don't limit freedom
  - Extending a concrete class is problematic (e.g., Properties, Timestamp, which we saw in the Equality lecture)

Why prefer **`implements A`** over **`extends A`**

- A class has exactly one superclass. In contrast, a class may implement multiple interfaces. An interface may extend multiple interfaces
- Interface inheritance gets the benefit of subtype polymorphism
  - And avoids the pitfalls of subclass inheritance, such as the fragile base class problem, etc.
- Multiple interfaces, single abstract superclass gets most of the benefit

Composition

- **`Properties`** is not a true subtype of **`Hashtable`**. Thus, cannot subclass. An alternative solution?
- Subclassing is a bad idea for the **`InstrumentedHashSet`** too. An alternative?
- **`Box`** is not a true subtype of **`BallContainer.`** Cannot subclass.
- Composition!

Properties Class from the JDK

`Properties` stores String key-value pairs. It extends **`Hashtable`** so **`Properties`** is a Java subtype of **`Hashtable`**. What's the problem?

```
class Hashtable {
 // modifies: this
 // effects: associates value with key
 public void put(Object key, Object value);
 // returns: value associated with key
 public Object get(Object key);
}
class Properties extends Hashtable { // simplified
 // modifies: this
 // effects: associates String value with String key
 public void put(String key, String value) {
    super.put(key, value);
 }
 // returns: value associated with key
 public String get(String key) {
    return (String) super.get(key);
 }
```

Properties

Wrapping class

The delegate

```
class Properties { // simplified

 private Hashtable ht = new Hashtable();

 // modifies: this
 // effects: associates value with key
 public void setProperty(String key,String value)
 {
    ht.put(key,value);
 }
 // returns: value associated with key
 public String getProperty(String key)
 {
    return (String) ht.get(key);
 }
```

InstrumentedHashSet

The delegate

```
class InstrumentedHashSet {
  private final Set s = new HashSet();
  private int addCount = 0;
  public InstrumentedHashSet(Collection c) {
   s.addAll(c);
  }
  public boolean add(Object o) {
   addCount++; return s.add(o);
  }
  public boolean addAll(Collection c) {
   addCount += c.size(); return s.addAll(c);
  }
  public int getAddCount() { return addCount; }
}
```

Box

The delegate

```
class Box {
  private BallContainer ballContainer;
  private double maxVolume;

  public Box(double maxVolume) {
    this.ballContainer = new BallContainer();
    this.maxVolume = maxVolume;
  }
  public boolean add(Ball b) {
   if (b.getVolume() + ballContainer.getVolume()
       > maxVolume)
    return false;
   else
    return ballContainer.add(b);
  }
  …
```

Composition

- <u>Implementation reuse without inheritance</u>
  - More common than reuse through subclassing
- Easy to reason about
- Works around badly-designed classes
- Disadvantages
  - Adds level of indirection
  - Tedious to write
  - Does not preserve subtyping

Composition Does not Preserve Subtyping

- **`InstrumentedHashSet`** is not a **`Set`** anymore
  - So can't substitute it
- It may be a true subtype of **`Set`**!
  - But Java doesn't know that
- That nice trick with interfaces to the rescue
  - Declare that the class implements interface **`Set`**
  - Requires that such interface exists